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# Precise Image-Based Motion Estimation for Autonomous Small Body Exploration

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## Motivation

Because they hold answers to questions about the origin of our solar system, comets and asteroids play an prominent role in NASA's roadmap for solar system exploration. NASA is planning multiple small body missions that range in scope from near body flybys to complete sample return. This paper presents an algorithm for autonomous onboard motion estimation that will enable the precision guidance and landing necessary for small body sample return.

Due to the small size, irregular shape and variable surface properties of small bodies, accurate motion estimation is needed for safe and precise small body exploration. Because of the communication delay induced by the large distances between the earth and targeted small bodies, landing on small bodies must be done autonomously using on-board sensors and algorithms. Current navigation technology does not provide the precision necessary to accurately land on a small bodies, so novel motion estimation techniques must be developed. Computer vision offers a possible solution to precise motion estimation.

Current missions require optical navigation for orbit determination and instrument pointing during close fly-bys of small bodies and moons of the outer planets. This is implemented by ground-based image processing to extract centroids of small reference targets like asteroids and moons. For the NEAR mission, orbit determination around asteroid Eros will use manual designation of known landmark features on the surface of the asteroid [1]. Limited automation will be introduced in the New Millennium DS-1 mission by implementing onboard centroiding of reference asteroids for autonomous navigation in small body fly-bys [2].

Proposed missions to explore comets and asteroids will not be able to rely on such techniques, because safe, precise navigation will require accurate knowledge of complex surface topography and because the round-trip light time will not allow this to be done on the ground. This paper describes a fully autonomous and onboard solution for accurate and robust motion estimation near a proximal small body. Our techniques are based on automatic feature tracking between a pair of images followed by two frame motion estimation and scale recovery using laser altimetry data. The output of our algorithm is an estimate of rigid motion (attitude and position) and motion covariance between frames. This motion estimate can be passed directly to the spacecraft guidance navigation and control system to enable rapid execution of safe and precise trajectories.

## Approach

Assuming that the spacecraft sensors are pointed at the small body surface, our algorithm works as follows. At one time instant a descent camera image and a laser altimeter reading are taken. A short time later, another descent camera image and laser altimeter reading are taken. Our algorithm then processes these pairs of measurements to estimate the rigid motion between readings. First, distinct features, which are pixels that can be tracked well across multiple images, are detected in the first image. Next, these features are located in the second image by feature tracking. Given these feature matches, the motion state and covariance of the spacecraft, up to a scale on translation, are computed using a feature-based motion estimation algorithm. Finally the scale of translation is computed by combining altimetry with the motion estimates using one of two complimentary methods depending on descent angle. These techniques are described in more detail below.

A feature is a pixel location and the surrounding image intensity neighborhood that can be tracked well across images that may under go arbitrary, but small, changes in illumination or viewing direction. A qualitative definition of a good feature is

an image region that has strong texture variations in all directions. For feature detection and tracking, we implemented the automatic feature detection method of Benedetti and Perona [3] which is a computation time optimized implementation of the well know Shi-Tomasi feature detector and tracker [4]. Since we know that the motion between images will be small, we used optical flow based methods for feature tracking; by minimizing the intensity difference as a function of feature translation between the two images, the location of the feature in the second image can be determined.

Using feature tracks, five of six motion parameters (change in attitude and direction of heading) can be estimated by minimizing a function that aligns features. For speed, a two step algorithm is used. First an estimate of the motion between frames is computed using a rapid, but less accurate, linear algorithm [5][6]. This algorithm is applied multiple times using different sets of features to eliminate feature track outliers and determine a robust LMedS estimate of motion. Next this motion estimate is input to a nonlinear motion estimation algorithm that minimizes directly the image distance between matched features. Output from the nonlinear algorithm is the estimate of the five motion parameters and their covariance.

The final stage of motion estimation computes the remaining motion parameter, magnitude of translation, from laser altimetry data. One of two complimentary methods is used. If images are taken as the spacecraft descends vertically to the surface, or the surface has very little surface relief, this computation is straightforward; the difference of the altimeter readings scaled by the cosine of descent angle is the magnitude of translation. If the spacecraft is not traveling directly toward the surface, or significant surface relief exists then a more complicated procedure must be used. From the feature-based motion estimate, the scaled range to a feature in the scene can be computed. Assuming the laser altimeter is aligned with the camera optical axis, features in the center of the image will have the same range as the laser altimeter reading. Consequently, the ratio of the laser altimeter reading to the scaled feature range will be the magnitude of translation. This approach requires only one altimeter reading, so it is not susceptible to errors from changing surface relief. Magnitude of translation when combined with feature-based motion determines the complete rigid motion of the spacecraft.

## Results

The algorithms above were coded and tested on real imagery acquired of a comet model built by a comet scientist at JPL. Altimeter readings were simulated by placing the camera on a translation stage and moving it toward the comet model by a known magnitude. The results show that the complete algorithm including feature detection, feature tracking and motion estimation provides motion estimates at 4Hz on an SGI R10000 processor for 640x480 images. The corresponding errors were 0.02cm over 1.0 cm (2.0%) for translation and 0.07 degrees for rotation.

A series of Monte Carlo tests were performed to determine the effect of sensor parameters, spacecraft trajectory and scene characteristics on the accuracy of comet relative motion estimation. To simplify the investigation, the space of possible motions was broken into two groups: descent (pure translational motion) and pointing (pure rotational motion). This simulation showed that the following motion accuracies were achievable with our algorithm: for vertical descent, a translational motion accuracy of 0.22 m at 1000 m when descending 65 m between frames (0.34%); a landing position accuracy from accumulation of vertical descent motion estimates of 3.6 m when descending from 1000 m (0.36%); and a rotational motion estimation accuracy of 0.006 degrees when pointing 0.6 degrees off of the optical axis.

## Conclusion

We have developed and tested a software algorithm that enables onboard autonomous motion estimation near small bodies using descent camera imagery and laser altimetry. Through simulation and testing, we have shown that visual feature tracking can decrease uncertainty in spacecraft motion to a level that makes landing on small, irregularly shaped, bodies feasible. Possible future work will include qualification of the algorithm as a flight experiment for the Deep Space 4/Champollion comet lander mission currently under study at the Jet Propulsion Laboratory.

## References


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